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Abstract: Aims: Clear-cutting is a common forest management practice, especially in subtropical China. However, the potential ecological consequences of clear-cutting remain unclear. In particular, the effect of clear-cutting on soil processes, such as the carbon cycle, has not been quantified in subtropical forests. Here, we investigated the response of soil respiration (Rs) to clear-cutting during a 12-month period in a subtropical forest in eastern China. Methods: We randomly selected four clear-cut (CC) plots and four corresponding undisturbed forest (UF) plots. Measurements of Rs were made at monthly time points and were combined with continuous climatic measurements in both CC and UF. Daily Rs was estimated by interpolating data with an exponential model dependent on soil temperature. Daily Rs was cumulated to annual Rs estimates. Important Findings: In the first year after clear-cutting, annual estimates of Rs in CC (508±23g C m−2 yr−1) showed no significant difference to UF plots (480±12g C m−2 yr−1). During the summer, soil temperatures were usually higher, whereas the soil volumetric water content was lower in CC than in UF plots. The long-term effects of clear-cutting on Rs are not significant, although there might be effects during the first several months after clear-cutting. Compared with previous work, this pattern was more pronounced in our subtropical forest than in the temperate and boreal forests that have been studied by others. With aboveground residuals off-site after clear-cutting, our results indicate that the stimulation of increasing root debris, as well as environmental changes, will not lead to a significant increase in Rs. In addition, long-term Rs will not show a significant decrease from the termination of root respiration, and this observation might be because of the influence of fast-growing vegetation after clear-cutting in situ.

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Effect of clear-cutting silviculture on soil respiration in a subtropical forest of China

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Abstract

Aims

Clear-cutting is a common forest management practice, especially in subtropical China. However, the potential ecological consequences of clear-cutting remain unclear. In particular, the effect of clear-cutting on soil processes, such as the carbon cycle, has not been quantified in subtropical forests. Here, we investigated the response of soil respiration to clear-cutting during a twelve-month period in a subtropical forest in eastern China.

Methods

We randomly selected four clear-cut plots (CC) and four corresponding undisturbed forest plots (UF). Measurements of soil respiration (Rs) were made at monthly time points and were combined with continuous climatic measurements in both CC and UF. Daily Rs was estimated by interpolating data with an exponential model dependent on soil temperature. Daily Rs was cumulated to annual Rs estimates.

Important findings

In the first year after clear-cutting, annual estimates of Rs in CC (508 ± 23 g C m^{-2} yr^{-1}) showed no significant difference to UF plots (480 ± 12 g C m^{-2} yr^{-1}). During the summer, soil temperatures were usually higher, whereas the soil volumetric water content (SVWC) was lower in CC than in UF plots. The long-term effects of clear-cutting on Rs are not significant, although there might be effects during the first several months after clear-cutting. Compared with previous work, this pattern was more pronounced in our subtropical forest than in the temperate and boreal forests that have been studied by others. With aboveground residuals off-site after clear-cutting, our results indicate that the stimulation of increasing root debris, as well as environmental changes, will not lead to a significant increase in Rs. In addition, long-term Rs will not show a significant decrease from the termination of root respiration, and this observation might be because of the influence of fast-growing vegetation after clear-cutting *in situ*.

Keywords: clear-cutting, subtropical forest, soil respiration, soil temperature

INTRODUCTION

Terrestrial ecosystems are one of the earth's most active carbon (C) reservoirs and thus play an important role in the global carbon cycle (Falkowski *et al.* 2000). Forests are particularly important ecosystems and contribute substantially to terrestrial C sequestration (Pan *et al.* 2011) by accumulating carbon in woody biomass and organic matter in mineral soil (Hamilton *et al.*, 2002; Harmon *et al.* 2004; Fahey *et al.* 2005). Excluding non-CO_2 fluxes in and out of the ecosystem, the net C balance of a forest can be approximated as the difference between CO_2 assimilation and CO_2 emission.

Anthropogenic disturbance of forest ecosystems, such as deforestation, can induce large net CO_2 emissions (van der Werf *et al.* 2009), both by directly releasing biomass carbon and by indirect CO_2 emissions from the accelerated decomposition of tree debris and soil organic matter (van der Werf *et al.* 2003). Thus, investigating how human activities, in particular deforestation, affect CO_2 emissions from soils (soil respiration, hereafter abbreviated as Rs) is of great importance to help us understand how soil processes may respond to abrupt environmental change.

Clear-cutting silviculture is an important forest management practice, especially in temperate and subtropical forests in China (Zhang, 2001; van der Werf *et al.* 2009). Clear-cutting affects Rs through several mechanisms. First, root respiration, which often contributes around half of soil respiration, will cease (Nakane *et al.* 1983). Second, the removal of aboveground biomass will lower or eliminate the flux of tree photosynthates to soils (Högberg *et al.* 2001) and thus reduce the associated microbial respiration. Third, changes in the spatial and temporal variability in soil temperature and moisture may also affect plant and soil microbial activities and thus alter Rs (Pierson *et al.* 1991; Flerchinger *et al.* 1997). Fourth, clear-cutting may also affect Rs by accelerating turnover rates of detrital and soil carbon pools including roots, litter, forest-floor organic matter, and mineral-soil organic matter (Lytle *et al.* 1998). Fifth, the management of clear-cutting, such as whether to remove the fallen debris or how to deal with productive weeds after clear-cutting, may also exert profound influences on Rs (Pumpanen *et al*. 2004; Busse *et al*. 2006). Therefore, predicting changes in Rs in the aftermath of clear-cutting is complicated and no consistent general trend has been found so far (Misson *et al.* 2005).

Subtropical forests in China generally consist of evergreen, broad-leaved species and are dominated by species of the genera *Castanopsis*, *Quercus* and *Schima* (Xiao *et al.* 2006; Legendre *et al.* 2009; Li *et al.* 2009). Moreover, fast-growing coniferous species, such as *Cunninghamia lanceolata* and *Pinus massoniana*, are common plantation species in this region. Most studies that have investigated the effects of clear-cutting forests on Rs have been carried out in coniferous forests of North America and Northern Europe (Olsson *et al.* 1996; Lytle *et al.* 1998; Striegl *et al.* 1998; Piirainen *et al.* 2002; Bekele *et al.* 2007). Only a few studies have addressed clear-cutting effects in subtropical forests (Guo *et al.* 2010), despite substantial differences in C cycling compared with temperate forests (Nakashizuka 1991; Baldocchi *et al.* 1996; Raich *et al.*

2002) and their importance for understanding of the global carbon cycle (Tang *et al.* 2006, Yi *et al.* 2007).

In 2008, a large collaborative project that addressed the effects of forest biodiversity on the functioning of ecosystem was established in east China (Bruelhelde *et al.* 2011). Before establishing artificial communities with 1–16 tree species, the broad-leaved secondary forest / conifer plantation monoculture of *Cunninghamia lanceolata* at the field site was clear-cut in February/March 2009 abiding by common forestry practice. Here, we investigated the effects of this clear-cutting from May 2009 to May 2010 by extrapolating single-time-point measurements of Rs to time-integrated measurements with an exponential model that was based on continuously recorded soil temperatures. Our goals were to (1) quantify CO_2 emissions from forest soils over time after clear-cutting; (2) analyze putative drivers of changes in Rs in different periods after clear-cutting, for example, soil temperature and moisture; and (3) compare the response of Rs to clear-cutting in subtropical forests with that in Northern coniferous forests, aiming to determine a proper explanation of the clear-cutting effects on both ecosystems.

MATERIALS AND METHODS

Field site and experimental design

The present study was conducted in a subtropical forest in Dexing County, Jiangxi Province, Eastern China (29º08′ N, 117º55′ E, Fig. 1a). The site is characterized by subtropical monsoon climate with mean annual precipitation (from 1994 to 2008) of ~2000 mm yr^{-1} and a mean annual temperature of 15.1°C (Geißler *et al.* 2010). The rainy season lasts from March to June, and sometimes September is also a rainy month. The field site has steep hills with an average slope inclination of 32º and spans an altitudinal range of 80 to 260 m a.s.l. The general slope aspect is toward the south with small-scale variation that is caused by several near parallel north-south ridges (von Oheimb *et al.* 2011). The soils at the field site are mainly Cambisols, which are mixed with Regosols on ridges and crests (Geißler *et al.* 2010).

Before clear-cutting, the study site was covered by a young, secondary, evergreen broad-leaved forest, with a high abundance of deciduous species (Wang *et al.* 2007). The tree species present included the evergreen broadleaved species *Castanopsis fargesii*, *C. sclerophylla*, *Lithocarpus glaber*, *Schima superba*, the deciduous species *Quercus fabri*, *Liquidambar formosana*, *Sassafras tzumu*, *Styrax dasyanthus*, *Sapium sebiferum*, *Diospyros kaki*, and the coniferous species *Pinus massoniana* and *Cunninghamia lanceolata* (von Oheimb *et al.* 2011).

From February to early March 2009, the 26.6 ha site was clear-cut, and all trees and shrubs were removed from the site until April (Fig. 1b). Starting in April 2009, a forest biodiversity experiment was conducted on the clear-cut area with young trees of 42 species that were planted in a quadratic grid pattern with a 1.29 m distance between individual trees. Additionally, due to the relatively high mortality rates of replanted trees, resowing work was performed in March 2010. For our study, four pairs of plots with an area of 100 m^2 each were established along the border of the clear-cut area in early May 2009. One of the plots in each pair was located within the clear-cut and re-planted area (CC), whereas the other plot was in the adjacent undisturbed forest (UF; Table 1). The aspect and inclination of each plot were measured using a compass. To standardize the effect of replanting, plot locations without fast-growing trees were selected. In fact due to the relatively high mortality rate of replanted trees in the first year, the effects of the replanted trees were quite limited during the experimental period. Weeds were removed in May and September 2009 by manually cutting aboveground herbs and woody plants except the planted ones.

Rs measurements

Soil respiration (Rs) was measured using a closed chamber that was connected to a portable infrared gas analyzer (LI-8100, Li-Cor Inc., Lincoln, Nebraska, USA). In each of the eight plots, eight chamber collars with a diameter of 20 cm and a height of 8 cm were installed along a transect with 1 m distance between collars. The chamber collars were permanently inserted 3 cm into the soil, thus protruding 5 cm above the ground. The first Rs measurement was carried out at least one day after the installation of collars.

From May 2009 to May 2010, Rs was measured once per month. These measurements were carried out three times per plot, at random hours during the daytime. Once per season, a 24-hour period respiration measurements were conducted at intervals of two hours.

Soil and air temperature and moisture

The soil temperature was measured at 5 cm depth using a thermometer probe that was connected to the portable soil respiration system. The soil temperature was measured simultaneously with the soil respiration measurement. Meanwhile, soil volumetric water content (SVWC) of the upper 10 cm was measured gravimetrically. In addition, six automatic data loggers were installed in three plot-pairs and recorded the soil and air temperature moisture at 30-minute intervals (EM50 data logger, Decagon Devices, Inc., Pullman, WA, USA): 1) a single combined air temperature/humidity sensor with a radiation shield was installed at a height of 1.5 m in the middle of each of the six plots; 2) three combined soil moisture/temperature sensors were installed at 5 cm, 10 cm and 20 cm soil depths in the middle of each of the six plots (ECH$_2$O soil moisture/temperature probes, Decagon Devices, Inc.). Precipitation was recorded by a weather station located in the middle of the entire clear-cut site.

Soil organic carbon and soil acidity

Soils cores with four replicates in each plot were collected in September 2010 and were divided into 0–5 cm, 5–10 cm and 10–20 cm depth sections. Total carbon (C) and nitrogen (N) concentrations were determined in these sections by an elemental analyzer (PE 2400 II CHN elemental analyzer, Perkin-Elmer, Boston, MA, USA). Soil pH was measured in the same samples by suspending fresh soil in deionized water at a 1:2.5 ratio (using 10 g subsamples of soil sieved through a sieve with 2 mm mesh size). Each suspension was allowed to stand for 30 min, and then the pH was measured potentiometrically (Table 1).

Statistical analysis

Rs data were analyzed using linear mixed-effects models with plot, collar, month and collar x months as random effects, and clear-cutting treatment, sine-transformed time since clear-cutting and the interaction between the two as fixed effects. Measurements of Rs were log-transformed prior to analysis to meet the requirements of normal distribution and homoscedasticity. For this dependent variable, soil temperature measured by the thermometer probe that was connected to the portable soil respiration system, was used as the covariate in an additional analysis. To check the responses of Rs in different periods after clear-cutting, we divided the whole experimental period into three periods: (1) first period, with increasing temperatures, starting one month after the clear-cutting and ending in the middle of summer 2009; (2) second period, with decreasing temperatures, running from late summer to the beginning of winter in 2009; (3) third period, with increasing temperatures, running from the beginning of 2010 until the end of May 2010. Mixed models were both built for the entire experimental period and for the first period for comparison. Considering the low replication at plot level and thus the relatively weak statistical power of the test for clear-cutting effects, we also report marginal significance ($P < 0.1$; see Toft and Shea (1983) for justification).

Modeled soil respiration (Rsm)

Soil respiration (Rsm) was modeled using the exponential equation given by Lloyd *et al.* (1994),

$$R_{sm} = R_{10} e^{E_0\left(\frac{1}{10-T_0} - \frac{1}{T-T_0}\right)} = R_{10} e^{E_0\left(\frac{1}{56.02} - \frac{1}{T-T_0}\right)}, \quad (1)$$

where R_{10} is Rsm at 10°C, T_0 and E_0 are two parameters that define the temperature-dependency of soil respiration. To facilitate the convergence of the non-linear regression procedure that was used to fit R_{10}, T_0 and E_0, we first estimated R_{10} and E_0 while fixing T_0 to –46.02 °C as proposed by Lloyd *et al.* (1994). We then re-started the non-linear regression using the solutions that were found for R_{10} and E_0; however, this time we also left T_0 free. For each plot in each of the three periods, we estimated the parameters separately using the corresponding measured Rs and soil temperature. The model fits were then based on hourly soil temperatures recorded by the automatic data loggers at a depth of 5 cm. Hourly Rsm values were modeled over the temperature range that was calibrated in equation (1). Daily Rsm values were calculated using hourly Rsm for each day.

The relative temperature sensitivity (RTS) of Rsm was also calculated as previously described by Hamilton *et al.* (2002):

$$RTS = \left(\frac{1}{f_{(T)}} \times \frac{df_{(T)}}{dT}\right) = \frac{E_0}{(T-T_0)^2} \quad (2)$$

For each period, RTS was also calculated separately.

Annual Rsm was estimated for each plot by calculating daily sums of Rsm using equation (1). The daily Rsm was then further summed to obtain seasonal and annual estimates of Rsm. Due to the lack of soil temperature records before July 2009, we used soil temperature data from the meteorological station in the middle of the clear-cut area. The corresponding soil temperatures in UF were predicted by comparing the soil temperature data in CC and UF in 2010.

All analyses were conducted using R 2.12.1 (The R Core Team 2011) and GenStat (VSN International, Hempstead, UK).

RESULTS

Microclimates in CC and UF

During the study period, the annual precipitation was 1225 mm in the year 2009, approximately half as much as the 2493 mm of annual precipitation in 2010, showing a strong inter-annual fluctuation (Fig 2a). Over the study period, the air temperature, soil temperature and SVWC all showed no significant differences between the CC and UF plots (t-tests). For both treatments, air temperature averaged 19.1 °C. Mean soil temperature at 5 cm depth was 19.3 °C, and mean SVWC was 28.6% (Fig 2b, c, d). However, in the summer of 2009 the mean soil temperature at 5 cm depth was 2.6 °C in the CC plots and was 2.6 °C higher than the mean soil temperature in the UF plots (t-test, $P < 0.05$), whereas the SVWC was approximately 6.7% lower (t-test, $P < 0.05$). In the summer of 2010, the mean soil temperature in the CC plots was 3.1 °C higher than the mean soil temperature in the UF plots (t-test, $P < 0.05$), but the SVWC showed no difference. In the winter, neither soil temperature nor SVWC differed significantly between the CC and UF plots.

Soil respiration

During the one-year experimental period, clear-cutting by itself did not show any significant effect on Rs in the linear mixed-model analysis. Rs averaged 0.94 μmol CO_2 m^{-2} s^{-1} in CC plots and 0.99 μmol CO_2 m^{-2} s^{-1} in UF plots (Table 3a). This observation was due to the very large and consistent variation in Rs between individual collars within plots (variance component 0.063 ± 0.013). However, when Rs measurements were first corrected for different soil temperatures as measured by the thermometer probe that was connected to the portable soil respiration system, clear-cutting led to a marginally significant decrease in soil respiration, averaging 0.89 µmol CO_2 m^{-2} s^{-1} in CC plots and 1.06 µmol CO_2 m^{-2} s^{-1} in UF plots (P = 0.08, Table 3b), suggesting that the similar values for uncorrected R_s measurements were due to higher soil temperatures in CC plots. The soil temperature as measured by the thermometer probe connected to the portable soil respiration system was significantly higher in CC than in UF plots (20.1 °C vs. 17.1 °C; P = 0.003, Table 3c).

According to the linear mixed-model analysis, clear-cutting by itself showed no significant effect on Rs during the first several months. However, the interaction between clear-cutting and month was still marginally significant (P = 0.072, Table 3d), suggesting that there indeed might have been a time-dependent effect of clear-cutting on Rs in this period. This interactive effect disappeared when correcting for soil temperature in the statistical model (Table 3e), suggesting that the detected interaction was caused by effects on temperature. Again, soil temperature as measured by the thermometer probe connected to the portable soil respiration system was significantly higher in CC than in UF plots (27.4 °C vs. 23.7 °C; P = 0.007, Table 3f).

In both the analysis of annual Rs and Rs in the first four months, the effects of the different collars and months were significant. In other words, there was considerable variation between collars within plot, whereas the temporal dynamics within collars were quite predictable (i.e., the individual measurements were not associated with a large random error).

Rsm modeling

During the whole experiment, mean Rs across four plots ranged from 0.19 ± 0.09 (mean ± SD) to 2.73 ± 0.98 μmol CO_2 m^{-2} s^{-1} in CC and 0.30 ± 0.10 to 2.07 ± 0.81 μmol CO_2 m^{-2} s^{-1} in UF. Rs showed a strong seasonal trend in both CC and UF plots (Fig. 3a). Parameters in Table 2 were used to estimate Rsm for individual plots during each period. Meanwhile, the differences in Rsm between two treatments were also calculated using modeled respiration values (Fig. 3b). As in the above mentioned results, Rsm in CC and UF plots showed changing trends during the first period after clear-cutting, whereas in the long-term, we assumed that Rsm in CC plots would eventually be lower than in UF plots. The annual cumulative carbon emission after clear-cutting was 508 ± 23 g C m^{-2} yr^{-1} in CC plots and 480 ± 12 g C m^{-2} yr^{-1} in UF plots. No significant difference was detected (Fig. 3c).

Relative temperature sensitivity (RTS) of Rsm

The relative temperature sensitivity (RTS) of soil respiration as a function of soil temperature was established separately for the three periods using Equation 2 and the parameters shown in Table 2 (Fig. 4). To compare the intrinsic temperature sensitivity in CC and UF plots during different times, we further tested the difference of mean RTS from 0 °C to 40 °C in CC and UF plots. During the first period when the temperature increased from the completion of clear-cutting in 2009 until the summer of 2009, temperature sensitivity in CC plots (0.069 °C^{-1}) was slightly higher than in UF plots (0.050 °C^{-1}, t-test, $P < 0.1$), whereas during the second period the temperature sensitivity was not different between treatments. For the last period, when the temperature in 2010 started to increase again until the summer of 2010, the temperature sensitivity in CC plots (0.067 °C^{-1}) was slightly lower than in UF plots (0.100 °C^{-1}, t-tests, $P < 0.05$).

DISCUSSION

Effects of clear-cutting on temperature and soil moisture

In our study, clear-cutting increased soil temperature in the summer but no corresponding effects were found in the winter. We argue that this effect occurs because in summer solar radiation dominates the soil temperature (Hashimoto *et al.* 2004), with clear-cutting eliminating the shading effect of the forest canopy (Flerchinger *et al.* 1997). It has been reported that the effect of leaf shading on soil temperature is evident (Kang *et al.* 2000). In contrast, winter soil temperatures are mainly controlled by the release of latent and sensible heat from the soil surface (Hashimoto *et al.* 2004). Therefore, in the winter the effects of solar radiation and forest canopy are not as strong as in the summer. Furthermore, deciduous species were relatively abundant in the studied forests, and leaf shedding before winter may also have reduced the effect of clear-cutting. Increased soil temperatures as consequence of clear-cutting have also been reported by Carlson *et al.* (1997), Hashimoto *et al.* (2004) and Pennock *et al.* (1997).

In contrast, clear-cutting decreased the summer SVWC in the first year. This result may be partly because the SVWC is indirectly determined to an extent by soil temperature (Breshears *et al.* 1998). Therefore, increased summer soil temperature after clear-cutting would result in a lower SVWC in CC than in UF. However, the difference of summer SVWC between two treatments disappeared in 2010. We assume that this disappearance may be because of the growth of trees that were replanted in March 2010; consequently, the differences between CC plots and UF plots were reduced. Interestingly, Covington (1981) and Redding *et al.* (2003) reported increased soil moisture in clear-cut plots, which were probably due to higher transpiration rates in UF plots compared with CC plots. In our study, continuous high precipitation limited the water sorption by roots in UF; thus, the reduction of SVWC that was caused by root absorption in UF is not significant (D'Odorico *et al.* 2007).

Effect of clear-cutting on soil respiration

In general, cumulated annual soil CO_2 emissions were not significantly affected by clear-cutting. However, this observation may not be simply illustrated as no influence because we did observe an effect of clear-cutting on Rs changing over time during the first four months. However, this effect disappeared when we tested for the entire experimental year. It has been extensively accepted that Rs is mainly comprised of root respiration and microbial respiration (Kuzyakov 2006). Root respiration usually ceases a short time after clear-cutting (Nakane *et al.* 1983; Ekblad *et al.* 2001; Högberg *et al.* 2001). Following this sudden decrease of Rs is the decomposition of dead roots and aboveground residuals under optimum temperatures, which consequently enhances microbial respiration (Kirschbaum 1995; Cortez 1998; Davidson *et al.* 2006; Hartley *et al.* 2008) and thus offsets the decline in root respiration (Ohashi *et al*. 2000). In this study, because all the aboveground residuals are carried off-site, root decomposition is of utmost importance when considering the increase in microbial respiration. Here, our results indicate that, for the initial four months (120 days), clear-cutting affected Rs differently over time. Considering that soil temperature and RTS in CC plots are consistently higher than in UF plots during this period, decomposition dynamics of the roots may be one main reason for the changing effect on Rs. A previous study found that roots were decomposed at different rates in different periods (Arunachalam *et al.* 1996).

However, the root decomposition becomes negligible typically after six months (Arunachalam *et al.* 1996). In our study, after the first period microbial respiration should slow down to its rate before clear-cutting and progressively decline, which would result in a decline in total Rs (Raich *et al.* 2000). However, such a decline does not occur during the experimental period, suggesting that there should be some other influencing factors. Although our results show a higher soil temperature in CC than UF plots during the third period, the corresponding lower RTS in CC plots indicates that a second increase in microbial respiration may not occur (Abbott *et al.* 1982, Binkley 1984). Meanwhile, the lower RTS in CC plots may also suggest a significant decline in roots (Boone *et al.* 1998; Davidson *et al.* 2006), verifying the termination of excessive decomposition. Therefore, we suggest that during these periods, the decline in root respiration is actually offset by the Rs of newly growing weeds and some other plants. In this study, weed residuals were not carried off-site, which may in turn enhance the microbial respiration in CC plots. Another possible reason why the response of Rs in the second year was different from the first year may be that after the first stimulating process of higher soil temperature, microbial respiration became acclimated to a higher soil temperature such that RTS decreased although the decomposition process actually continued (Luo *et al.* 2001). Nonetheless, it is necessary to examine the effect of clear-cutting on Rs during different periods, instead of looking at the whole process.

Similar patterns have been reported among the limited number of studies that tested the clear-cutting effect on Rs in subtropical forests. For example, Guo *et al.* (2010) found that clear-cutting increased Rs for the first 3 months immediately after treatment; however, for the subsequent 2 years the Rs in CC plots fell below that of UF plots. Ponder (2005) also measured Rs after clear-cutting in a hardwood forest in Missouri. Although Rs did not change for the first 2 months immediately after treatment, for the subsequent several months the Rs in CC decreased below UF, which also indicated a staged response of Rs to clear-cutting. Such results confirmed the time-dependent effect of clear-cutting on Rs. However, considering that for different ecosystems the percentage of root respiration is considerably different (Pumpanen *et al*. 2004), it is reasonable that discrepancies exist among different studies for the first several months.

Effects of clear-cutting on Rs in different ecosystems

Most previous studies were conducted in northern coniferous forests, which showed highly variable responses of R_s to clear-cutting (Lytle *et al.* 1998; Startsev *et al.* 1998; Striegl *et al.* 1998; Kim 2008; Zu *et al.* 2009). As illustrated in the second part of discussion, clear-cutting affects Rs through several processes that are related to changes in soil microclimates, substrate availability, and also microbial activity (Deluca *et al.*, 2000). Such processes may differ among regions (Kirschbaum 1995) and also forest types (Cortez 1998; Prescott *et al.* 2000). Generally, subtropical forests are characterized by high annual average temperatures and large variations in temperature (Hashimoto *et al.* 2004) compared with temperate forests and boreal forests where mean annual temperatures arerelatively low and variations in temperature are small (Davidson *et al.* 1998; Bowden *et al.* 2004). In boreal forests, there even exists a long period when the soil temperature drops below 0 °C (Rayment *et al.* 2000). The general response of Rs to clear-cutting could be significantly influenced by soil temperature, and the sensitivity of soil to temperature changes also varies among different regions (Kirschbaum 2000). Therefore temperature may impact Rs after clear-cutting through different ways in different forest types: (1) Clear-cutting elevated soil temperature and enhanced soil temperature sensitivity, so that microbial respiration increases and lasts for a long time because soil temperature does not vary significantly, such as in subtropical forests. In this case, Rs may show an increasing trend in the observation period after clear-cutting; (2) Clear-cutting raises soil temperature and soil temperature sensitivity; however, other influencing factors may inhibit the stimulation effect, such as a lower soil surface SVWC caused by clear-cutting in some regions like coniferous forests (Prescott 1997). In this case, soil respiration may be restrained. Moreover, the fast-growing weeds after clear-cutting might also be an important factor in our study because in Northern forests the growth rates of weeds are usually lower than in subtropical forests and may consequently have less influence on Rs. To summarize, many factors such as soil temperature, SVWC, and substrate availability, as well as other unknown factors, may exert an influence on Rs (Kirschbaum 1995; Cortez 1998; Giardina *et al.* 2000; Holland *et al.* 2000); thus, there have been inconsistent results in different forest ecosystems.

In addition, the time interval between clear-cutting and the start of investigation may also influence the observed pattern of Rs. Many studies began recording Rs half a year or one year after clear-cutting (Startsev *et al.* 1998; Striegl *et al.* 1998; Kim 2008), when Rs had already attained a steady state even if a stimulation period existed in such ecosystems at the beginning of clear-cutting. In contrast, Guo *et al.* (2010) and our study provided a relatively short time interval between the study and clear-cutting so that a staged pattern of Rs change was observed.

Limitations of the current study

In the present study, we only have four blocks, which may not be sufficient to eliminate the heterogeneity of sites. Meanwhile, from the results of mixed effect models, the small-scale heterogeneity in Rs among collars was large. According to previous studies, the distribution of plant roots, leaf litters, the depth of soil organic horizon and the distance of measuring point from trees, all lead to Rs heterogeneity (Stoyan *et al.* 2000; Scott-Denton *et al.* 2003; Tang *et al.* 2005a). Moreover, the dependence of Rs on different environmental factors also vary among different spatial scales (Reichstein *et al.*

2008). Therefore, more study plots in the future studies should be established; and furthermore, determining how to estimate Rs with proper models including the environmental factors at small scales may be of utmost importance. In addition, more studies are required to further understand the whole subtropical forest by a comparison with temperate forests and boreal forests (Adachi *et al.* 2005). With respect to the temporal scale, this experiment lasted only one year. Considering that 2009 was a particularly dry year, the results may be partly influenced by the abnormal climate conditions; therefore, an additional year-long study is necessary to further confirm the conclusions. Additionally, the measuring interval of this study was one month, which may not be sufficient to describe all the changing processes of Rs. In that case, a continuous Rs measuring technique will improve the model of soil respiration and will offer a more precise prediction of the total emission CO_2 flux, especially for long-term observation (Tang *et al.* 2005b).

CONCLUSIONS

Rs in the subtropical forest in Xingangshan showed an obvious seasonal trend in both CC and UF plots, in accordance with variation of soil temperature at the two sites. Temperature is the main factor influencing Rs rates in both CC and UF plots. In the short-term, clear-cutting has a significant influence on Rs changing over time due to the uncertainty of root decomposition within several months after clear-cutting; however, in the long-term, clear-cutting has no significant effect on soil respiration due to the balance between reduction of root respiration and the increase in Rs from fast-growing weeds and other plants. Moreover, soil temperature sensitivity increases during the first several months after clear-cutting and decreases gradually afterwards, eventually dropping to a lower level than before clear-cutting. Comparing with studies that have been carried out in other regions and forest types, we suggested that the response of Rs to clear-cutting might be influenced by different factors among different forest types.

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Tables

Table 1. Site characteristics and soil properties for clear-cut (CC) and undisturbed-forest (UF) plots at the end of the experiment. Standard errors of means are given in parentheses.

	CC plots (n = 4)	UF plots (n =4)
Altitude (m)	168-204	169-268
Inclination (°)	15-45	5-30
Soil organic C (%)		
0-5 cm	2.83 (0.13)	3.04 (0.08)
5-10 cm	1.83 (0.15)	1.92 (0.08)
10-20 cm	1.46 (0.12)	1.38 (0.19)
Soil total N (%)		
0-5 cm	0.24 (0.02)	0.24 (0.02)
5-10 cm	0.16 (0.02)	0.16 (0.01)
10-20 cm	0.11 (0.02)	0.12 (0.02)
Soil pH		
0-5 cm	6.22 (0.15)	6.19 (0.14)
5-10 cm	6.24 (0.13)	6.23 (0.10)
10-20 cm	6.14(0.16)	6.25 (0.08)

Table 2. Fitted parameters (standard errors in parentheses) for modeled soil respiration ($Rsm = R_{10}e^{E_0(\frac{1}{283.15-T_0}-\frac{1}{T-T_0})}$) in clear-cut (CC) and undisturbed-forest (UF) plots. Data are shown for the three periods defined in the text. * indicates a significant difference between two treatments.

	Temperature increasing period in 2009		Temperature decreasing period in 2009		Temperature increasing period in 2010	
Dates	May – August, 2009		September – January, 2010		February – May, 2010	
Plot	CC	UF	CC	UF	CC	UF
R_{10} (μmol CO_2 m^{-2} s^{-1})	0.377 (0.017)	0.353 (0.017)	0.327 (0.041)	0.366 (0.020)	0.307 (0.020)	0.380 (0.040)
E_0 (K)	312.6 (2.8)	281.3 (8.6)	303.5 (20.7)	286.2 (11.3)	313.7 (16.4) *	432.0 (11.8)
T_0 (°C)	-50.4 (0.5)	-60.7 (3.5)	-65.3 (7.1)	-59.5 (2.8)	-53.4 (2.0)	-49.1 (0.5)

Table 3. Results of mixed-model analyses for soil respiration with and without correction for soil temperature during the entire experimental period and period one (May to September, 2009). Variance components that are about twice the size of their standard errors can be considered significant; n.d.f. = nominator degree of freedom, d.d.f. = denominator degree of freedom.

a) Rs uncorrected for soil temperature during the whole experimental period:

Random terms:	variance component	standard error of v.c.
Plots (8-levels factor)	0.0120	0.0163
Collars within plots (8-levels factor)	0.0627	0.0130
Months (12-levels factor)	0.0282	0.0182
Collars within plots x Months	0.0660	0.0138

Fixed terms:	Wald statistic	n.d.f.	F-value	d.d.f.	*P*
Treatment (CC vs. UF)	0.31	1	0.31	5.9	0.60
Sine-transformed months (variate)	89.69	1	89.69	10.0	<0.001
Treatment x sine.tr. months	1.11	1	1.11	56.3	0.3

b) Rs corrected for soil temperature during the whole experimental period:

Random terms:	variance component	standard error of v.c.
Plots (8-levels factor)	0.0122	0.0151
Collars within plots (8-levels factor)	0.0619	0.0128
Months (12-levels factor)	0.0149	0.0110
Collars within plots x Months	0.0465	0.0102

Fixed terms:	Wald statistic	n.d.f.	F-value	d.d.f.	*P*
Temperature (covariate)	174.50	1	174.50	613.7	<0.001
Treatment (CC vs. UF)	4.42	1	4.42	6.2	0.08

Sine-transformed months (variate)	18.75	1	18.75	31.5	<0.001
Treatment x sine.tr. months	0.11	1	0.11	56.7	0.75

c) Rs uncorrected for soil temperature during period one (May to September, 2009):

Random terms:	variance component	standard error of v.c.
Plots (8-levels factor)	0.0025	0.0114
Collars within plots (8-levels factor)	0.0647	0.0133
Collars within plots x Months	0.0185	0.0088

Fixed terms:	Wald statistic	n.d.f.	F-value	d.d.f.	*P*
Treatment (CC vs. UF)	0.22	1	0.22	5.9	0.65
Sine-transformed months (variate)	22.84	1	22.84	11.1	<0.001
Treatment x sine.tr. months	3.95	1	3.95	11.1	0.07

d) Rs corrected for soil temperature during period one (May to September, 2009):

Random terms:	variance component	standard error of v.c.
Plots (8-levels factor)	0.0050	0.0130
Collars within plots (8-levels factor)	0.0646	0.0133
Collars within plots x Months	0.0182	0.0088

Fixed terms:	Wald statistic	n.d.f.	F-value	d.d.f.	*P*
Temperature (covariate)	23.90	1	23.90	266.3	<0.001
Treatment (CC vs. UF)	0.58	1	0.58	6.8	0.5
Sine-transformed months (variate)	5.38	1	5.38	21.9	0.030
Treatment x sine.tr. months	2.73	1	2.73	11.1	0.13

Table 4. Results of mixed-model analyses for soil temperature during the entire experimental period and period one (May to September, 2009). Variance components that are about twice the size of their standard errors can be considered significant; n.d.f. = nominator degree of freedom, d.d.f. = denominator degree of freedom.

a) Soil temperature during the whole experimental period:

Random terms:	variance component	standard error of v.c.
Plots (8-levels factor)	0.127	0.384
Collars within plots (8-levels factor)	0.007	0.015
Months (12-levels factor)	2.971	1.740
Collars within plots x Months	4.762	0.917

Fixed terms:	Wald statistic	n.d.f.	F-value	d.d.f.	*P*
Treatment (CC vs. UF)	23.79	1	23.79	5.9	0.003
Sine-transformed months (variate)	131.15	1	131.15	9.7	<0.001
Treatment x sine.tr. months	4.72	1	4.72	56.9	0.034

b) Soil temperature during period one (May to September, 2009):

Random terms:	variance component	standard error of v.c.
Plots (8-levels factor)	-0.0514	0.9012
Collars within plots (8-levels factor)	0.0003	0.0244
Collars within plots x Months	3.3250	1.4501

Fixed terms:	*Wald statistic*	*n.d.f.*	*F-value*	*d.d.f.*	P
Treatment (CC vs. UF)	18.47	1	18.47	5.3	0.007
Sine-transformed months (variate)	44.52	1	44.52	11.8	<0.001
Treatment x sine. tr. months	2.09	1	2.09	11.8	0.18

Figure legends

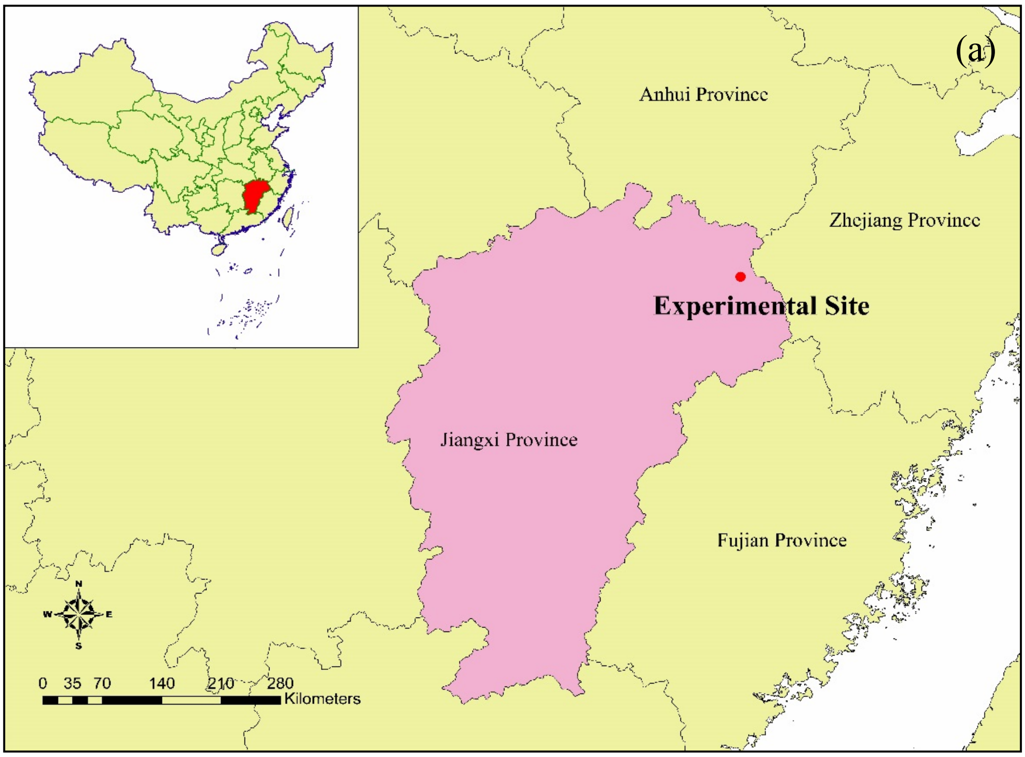
Fig. 1 Location (a) and the landscape of the experimental site (b). The study area is in Jiangxi Province, East China. The picture of the landscape was taken in May 2009, one month after the completion of clear-cutting.

Fig. 2 Rainfall (a), air temperature (b), soil volumetric water content (SVWC) (b) and soil temperature at -5 cm during the experimental period from March 2009 to November 2010. Rainfall was recorded by an on-site climate station. Red solid lines represent CC; black solid lines represent UF. SVWC was recorded by Decagon ECH_2O sensors with data logger EM50. In figure 2b, 2c and 2d, shadow parts represent the error bar that show the standard error for each line.

Fig. 3 Soil respiration measured at CC and UF plots together with soil respiration which was modeled from 2009 to 2010 using a flexible exponential equation at two sites (a), the increasing amount of soil respiration calculated using modeled soil respiration rates (b) and the cumulative CO_2 flux calculated from modeled soil respiration rates through the whole experimental period (c). In figure 4a, empty red circles refer to observed soil respiration and solid red lines represent modeled soil respiration at CC; empty black circles refer to observed soil respiration and solid black lines represent modeled soil respiration at UF. In all the three subfigures, shadow parts represent the error bar that show the standard error for each line.

Fig. 4 Relative temperature sensitivity (RTS) as a function of soil temperature. (a), temperature-increasing period from May to August 2009; (b), temperature-decreasing period from September 2009 to January 2010, and (c), temperature-increasing period from February to May 2010. Red lines refer to CC; black lines represent UF. In all the three subfigures, shadow parts represent the error bar that show the standard error for each line.

Fig. 1


(a)
Anhui Province
Zhejiang Province
Experimental Site
Jiangxi Province
Fujian Province
N
W
E
S
0 35 70 140 210 280
Kilometers

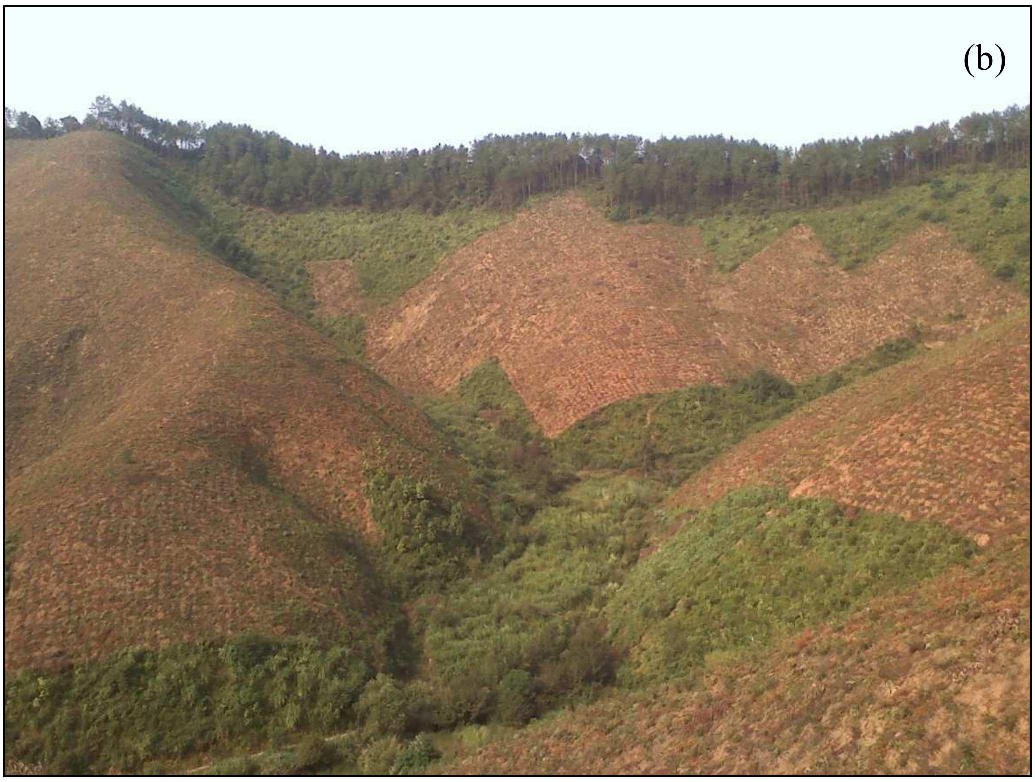
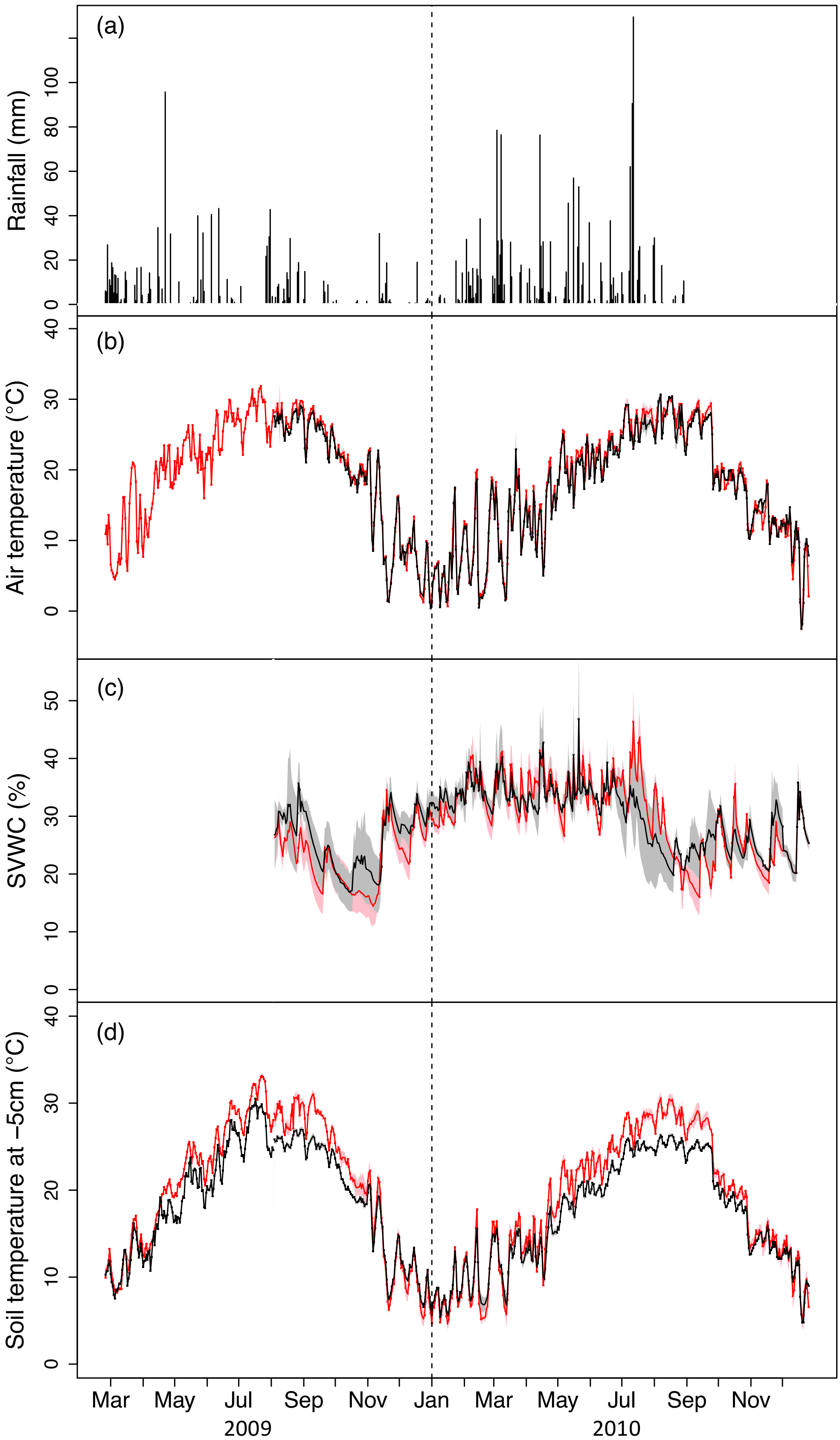
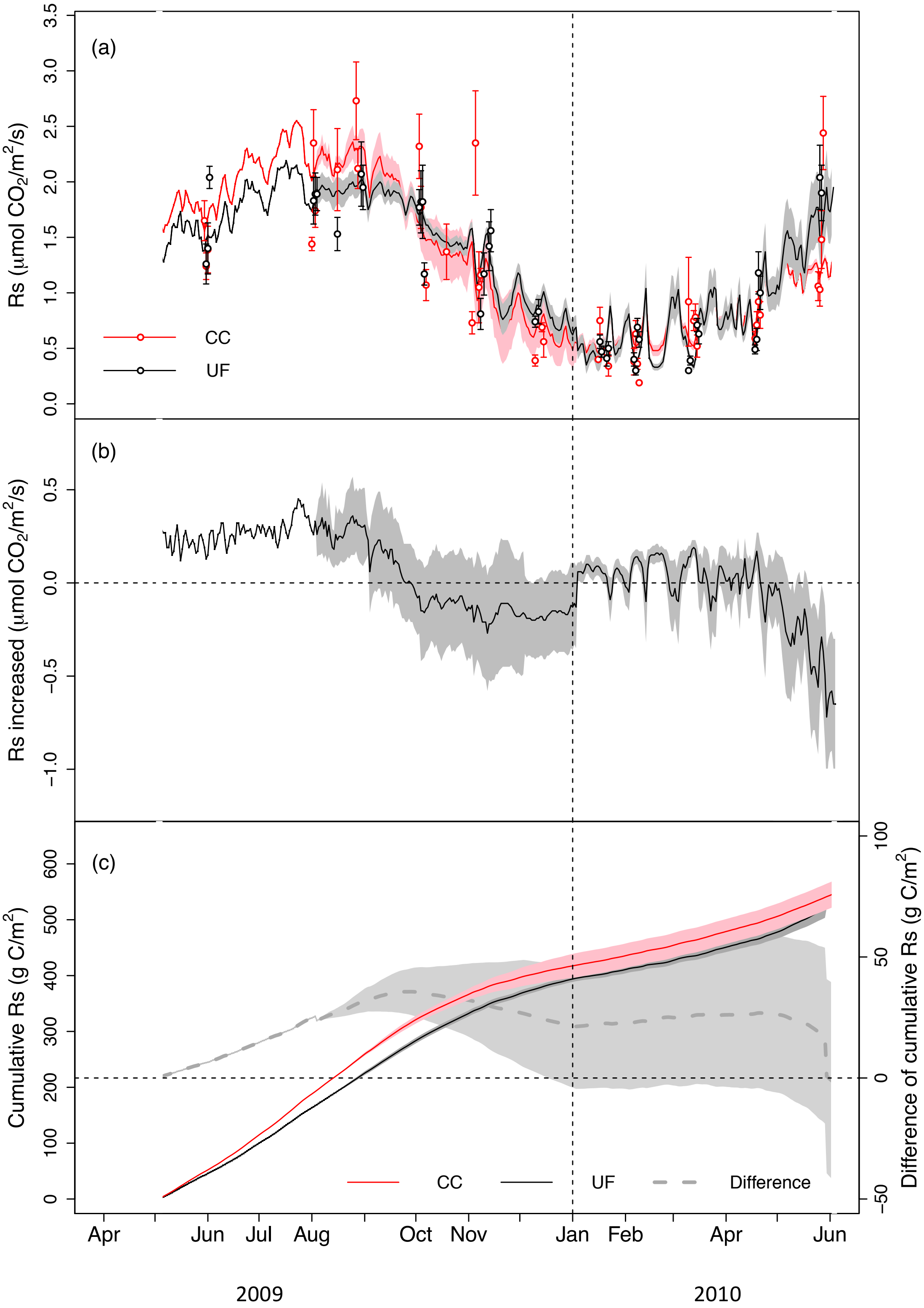

(b)

Fig. 2



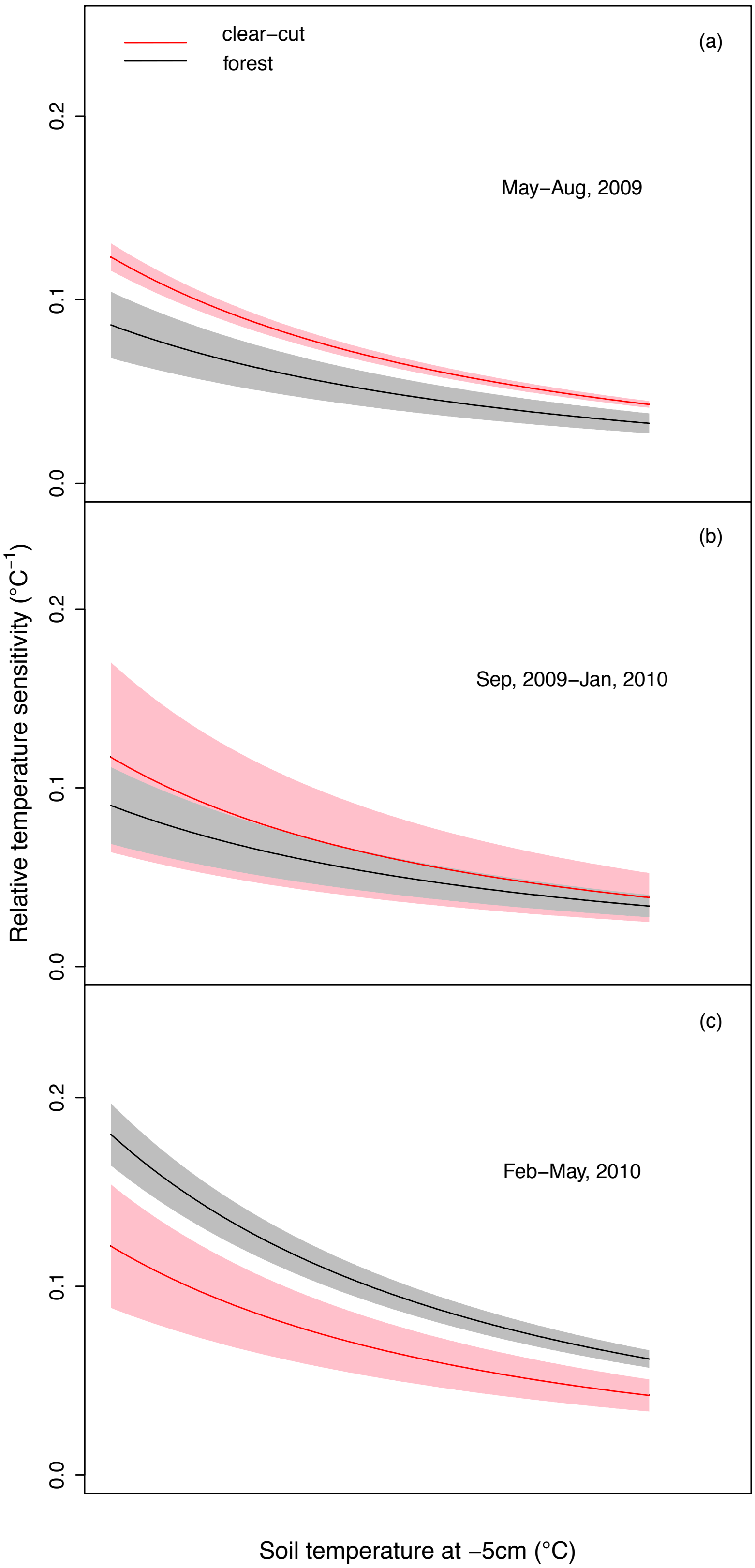
(a)
Rainfall (mm)
0
20
40
60
80
100
(b)
Air temperature (°C)
0
10
20
30
40
(c)
SVWC (%)
0
10
20
30
40
50
(d)
Soil temperature at −5cm (°C)
0
10
20
30
40
Mar
May
Jul
Sep
Nov
Jan
Mar
May
Jul
Sep
Nov
2009
2010

Fig. 3



(a)
Rs (µmol CO2/m2/s)
CC
UF
(b)
Rs increased (µmol CO2/m2/s)
(c)
Cumulative Rs (g C/m2)
Difference of cumulative Rs (g C/m2)
CC
UF
Difference
Apr
Jun
Jul
Aug
Oct
Nov
Jan
Feb
Apr
Jun
2009
2010

Fig. 4



clear–cut
forest
(a)
May–Aug, 2009
(b)
Sep, 2009–Jan, 2010
(c)
Feb–May, 2010
0.0
0.1
0.2
Relative temperature sensitivity (°C^{-1})
Soil temperature at –5cm (°C)